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# PART II - EFFECTS OF CROSS-SECTIONAL PARTITIONING ON ACTIVE NOISE CONTROL IN ROUND DUCTS

by

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# ABSTRACT

Active noise control (ANC) is particularly useful in hard-walled ducts where plane waves propagate. Higher order mode waves are much more difficult to control. Basic acoustic principles dictate that the cut-on frequency at which higher order modes will first begin to eclipse simple plane waves in a duct will be determined by the cross-sectional diameter of the duct. The lowest frequency for higher order modes will increase as duct diameter decreases. Therefore, the range of frequencies where plane waves dominate will be greater and effective control using ANC better as duct diameter decreases. The result is that somewhat higher frequencies can be controlled with ANC for smaller diameters. If smaller diameters have broader frequency ranges that can be controlled with ANC, perhaps one could extend the frequency range for a large cross-section by partitioning it into smaller cross-sections. This hypothesis was tested by two methods of cross-sectional partitioning. Partitioning was achieved in one design by inserting a smaller duct inside a large duct. In a second design, a cross-shaped partition was inserted inside the large duct. ANC IL results were 1.7 to 2 dB better for the large duct partitioned by a smaller inner duct than the large duct alone ($p=0.0146$ for low frequency and $p=0.0333$ for high frequency). ANC insertion loss was 5.8 dB better for the large duct partitioned by a cross-shaped splitter at high frequencies than the large duct alone ($p=0.0003$). However, the cross-shaped partition system was 5.6 dB less effective at low frequencies than the large duct ANC IL alone ($p<0.0001$).

# INTRODUCTION

Plane waves are simple to control because the movement of the wave down the duct can be easily predicted from the length of the duct and the speed of sound. Higher order modes are erratic and therefore difficult to predict and control. As a result many sensors (such as microphones) and control speakers are needed to sample and counter higher order modes (Mazanikov et al., 1977; Eriksson et al., 1989; Zander and Hansen, 1992; Pelton et al., 1994). Therefore, if the frequencies involved are largely limited to those producing plane waves, ANC is more likely to produce substantial insertion losses.

Besides recognizing that plane waves are easier to control, many researchers also mention axial vane splitters as a method to prevent higher order modes from dominating plane waves at higher frequencies. Eghtesadi *et al.* (1986) actually split an HVAC duct to reduce higher order mode concerns. Egaña *et al.* (1989) used an HVAC duct from a train car that was already split by design. Eriksson *et al.* (1989) focused on higher order mode control, but mentioned that axial splitters would be a common method to prevent higher order mode propagation. Earlier mention of axial vane splitters by Cullum (1949) and Beranek (1960) was solely to facilitate passive noise controls by increasing the absorptive surface area inside the duct.

After reviewing the literature, no diameter effects studies or cross-sectional partitioning strategy studies were found except Eghtesadi *et al.*'s (1986) study on energy conservation. The data obtained from such experiments would aid in devising simple ANC solutions for large duct broadband noise problems so often encountered in industry.

Two methods used to reduce duct dimensions without reducing total cross-sectional area are (1) using many smaller ducts for the same volumetric flow as in Figure 1 or (2) using axial vane splitters for cross-sectional partitioning as in Figure 2. It is not always practical to substitute several smaller diameter ducts for a larger one since the pressure due to air flow is proportional to diameter to the 1.2 power (Guffey and Hickey, 1983). (Note that Guffey and Hickey (1983) report that using a single smaller duct with the same flow would change the pressure by the diameter ratio to the 4.5 power.) While splitters have been used to increase surface area of acoustically absorptive material in ducts for some time (Cullum, 1949; Beranek, 1960), there is only one study applying them to active noise control (Eghtesadi et al, 1986).

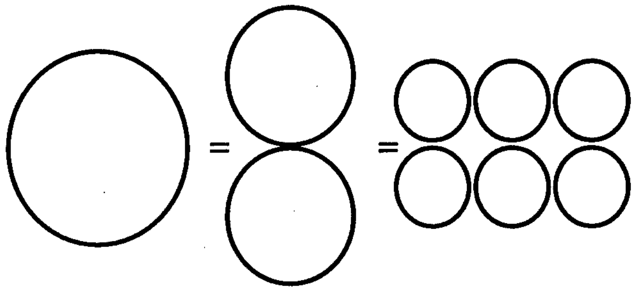

Figure 1. Equivalent volumetric round ducts

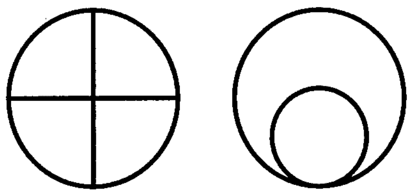

Figure 2. Cross-sectional partitioning schemes for round ducts

### Problem Statement

The research presented here attempted to extend the usefulness of ANC in large ducts by exploring the effects of cross-sectional partitioning on ANC insertion loss in large ducts. The initial information gathered from cross-sectional dimension studies in both rectangular and round ducts in Part I was used to help design cross-sectional partitioning experiments that focused only on round ducts.

## COMMON ANC APPARATUS

The active noise control test device was common throughout all studies and is discussed in this section. The apparatus difference between the studies was in the different ducts used. The unique apparatuses for each study are presented in the individual chapters pertaining to those studies.

The simple active noise control (ANC) system sketched in Figure 3 was used for the experiments described here. The components consisted of a source speaker attached tightly to one end of the various ducts with a directional reference microphone next to the source speaker in the tube. The ¼" array microphone (PCB Piezotronics, Depew, NY) was made directional by inserting it into a ½" I.D. four foot long X5305 microporous tube (Porex, Atlanta, GA). A directional reference microphone preferentially senses the source speaker wave impinging at the tip and was necessary to prevent feedback from the control speaker noise broadcast at the other end of the duct reaching the reference microphone.

The source speaker signal was random broadband white noise generated by a signal generator on an OR-38 (OROS, Falls Church, VA) real-time analyzer (RTA). The reference microphone signal was fed into the EZ-ANC II active noise controller (Causal Systems, Inc., Adelaide, Australia) which used a "filtered-x" control algorithm to determine the signal generated for the control speaker to counter the noise coming down the duct. Another ¼" array microphone (PCB Piezotronics, Depew, NY) was used as the "error" microphone (see Figure 6) to detect the residual sound after control (i.e., the sound not "cancelled" by the downstream speaker). The active noise controller dynamically adjusted the signal sent to the control speaker to minimize the residual sound. For the experiments, the error microphone signal was split off to the real-time analyzer to provide a result reading (with and without ANC).

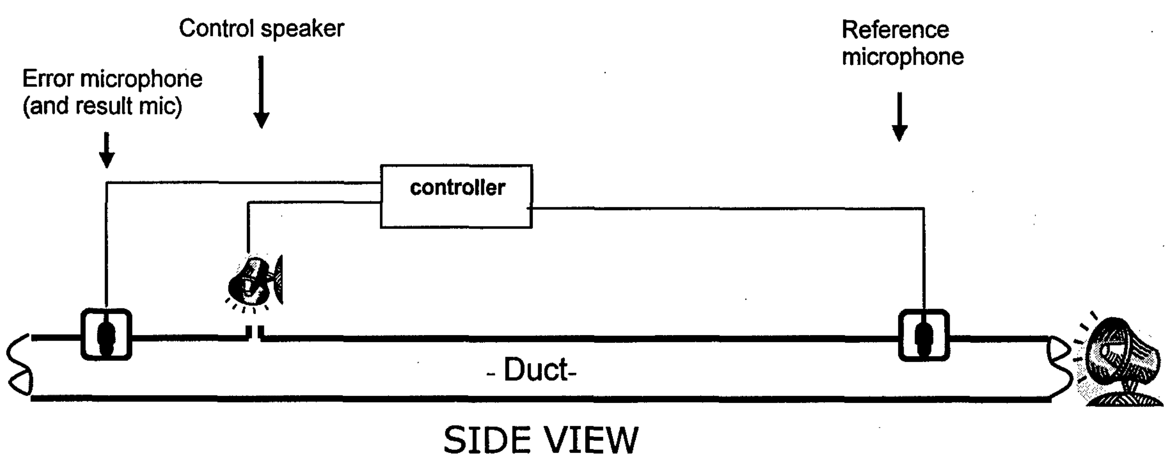


Figure 3. Experimental apparatus

## Variables and Hypotheses

The two dependent variables monitored were the insertion loss at two different frequency ranges. One-third octave band values, with ANC on, were subtracted from the same bands with ANC off to give a measure of insertion loss for each 1/3 octave band. The maximum insertion loss values among the frequency focus bands were recorded for each 1/3 octave band. The insertion loss values were then summed from 20-250 Hz as a low frequency $IL_{max}$ value, and summed from 315-5000 Hz as a high frequency $IL_{max}$ value. These two values, $IL_{max} \leq 250$ Hz and $IL_{max} \geq 315$ Hz, were the dependent variables.

There are numerous independent variables that affect the $IL_{max}$ results for ANC of random noise in ducts. The independent variables of bandwidth, ANC controller operation, and software settings were held constant. Microphone position was held constant during each individual study. The remaining independent variables were: inner duct diameter for two-duct studies, simultaneous operation of two ducts, simultaneous operation with a reduced hardware configuration, and finally a cross-shaped splitter in a round duct. As these were too many variables to analyze in a single study, a series of studies was devised to address one independent variable at a time. The studies with variables, null hypotheses, and test type are listed in Table 1.

Table 1. Series of studies to describe independent variables

| Study | Variable | $H_0$ | Test |
|---|---|---|---|
| II | Inner duct diameter | No effect of inner duct diameter | 1-way ANOVA |
| IIIa | Simultaneous operation | No difference between 18" duct alone and 2 ducts simultaneously | t-test |
| IIIb | Hardware combination | No difference between 18" duct alone and 2 ducts with single reference microphone | t-test |
| IV | Cross-shaped splitter | No difference between 18" duct alone and single quadrant area | t-test |

The series of studies was designed to describe the effects of cross-sectional partitioning on active noise control in round ducts. Each study was treated in a separate section to adequately describe the unique apparatus/methods, results, and discussion for each independent variable.

# Study II: INNER DUCT DIAMETER

### Study II Unique Apparatus

Study II was designed to test the effect on ANC insertion loss efficacy of inserting a smaller diameter round duct inside an 18 inch diameter round duct. A large 18 inch diameter round duct was used as the outer duct. Then different smaller diameter round ducts were inserted into the 18 inch duct to create cross-sectional partitions. The $IL_{max}$ was compared between different smaller duct diameters as the treatment group and also to the 18 inch large duct alone using multiple comparison techniques.

The smaller inner ducts were capped at the end facing the source speaker to reduce the sound transmitted down their interior that might radiate back into the outer duct space (see Figure 4). Since Part I established the ANC IL of different diameter round ducts, Study II was not concerned with the ANC IL of the smaller inner ducts but of the outer duct space left after the smaller ducts were inserted.

The large outer duct was 20 ft long in four 5 ft sections up to a "tee" as in Figure 6. The tee was also 18 inches in diameter, with a 4 inch diameter perpendicular branch 8 inches long for the control speaker input to the system. The tee was 2 ft long. After the tee, an additional 5 ft length of 18 inch diameter duct was added with acoustic foam at the far end to reduce reflections. All junctions between 5 ft sections were sealed with gasketed clamps. The control speaker was held in place with gravity and a gasket that sealed the air space between the speaker and the 4 inch diameter tee branch. Microphones were suspended 2 inches below the top of the 18 inch duct directed toward the source speaker. The microphones were suspended by nonconductive means (duct tape attached to foam holder) so that duct surface vibration would not transfer to and contaminate the microphone signals.

The inner ducts were similar to the 18 inch duct except they were straight runs of sealed, clamped duct 25 ft long with no tee. The effect of the position of the duct, whether concentric to or sitting at the bottom of the outer duct (tangent), was investigated in a preliminary experiment. There was no significant difference between the IL achieved at the concentric vs. tangent inner duct positions, so the tangent position was selected for the study. The tangent inner duct position would provide an easy access for control speakers to the inner duct space in application.

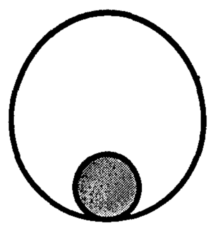

Figure 4. Study II Apparatus, End view of inner duct position

Study II investigated the effect of different diameter inner ducts on the ANC IL in the remaining area of the 18 inch diameter outer duct as shown in Figure 5. The inner ducts were 6 inch, 8 inch, 12 inch, and 16 inch diameter. The empty 18 inch diameter outer duct was also tested as a treatment group with which to compare all other treatments.

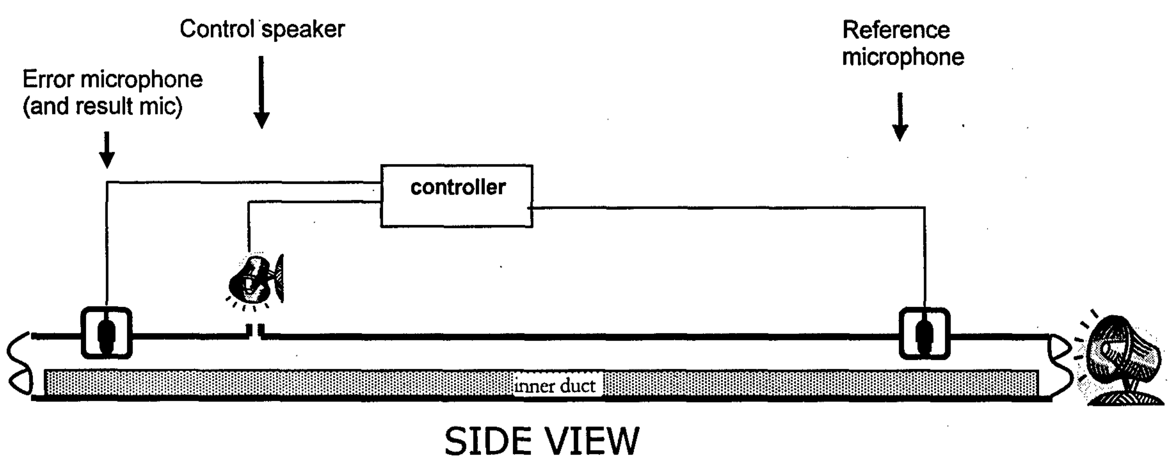


Figure 5. Study II Apparatus, Side view of inner duct diameter apparatus

### Study II Model and Study Design

Study II was designed to test the hypothesis that there was no effect on $IL_{max}$ in the remaining crescent-shaped open cross-section of the large diameter 18 inch outer duct from changing the diameter of the inner duct. Tested inner diameters were zero inch (no-inner-duct), 6, 8, 12, and 16 inches. Based on preliminary findings, all inner ducts were positioned tangent to the bottom of the outer duct. Since the only effect being studied was the inner duct diameter effect, a single factor fixed effects model was sufficient for the study design. The statistical model assumed was:

$$IL_{ij} = \mu + \tau_i + \varepsilon_{ij}$$

Where:

$IL_{ij}$ = insertion loss in decibels (dB)
$\mu$ = average insertion loss for all treatments
$\tau_i$ = effect of the $i^{th}$ inner diameter, $i = 1, 2, \ldots, a$
$\varepsilon_{ij}$ = random error, $j = 1, 2, \ldots, n$

This model was used to test the following hypothesis on the effect of diameter:

$H_0$: $\tau_1 = \tau_2 = \ldots = \tau_a = 0$

$H_1$: at least one $\tau_i \neq 0$

Stated non-mathematically, the hypothesis was:

$H_0$: No effect of inner duct diameter
$H_1$: At least one inner duct diameter different

Power calculations indicated that, given the average variability in the preliminary tests ($\Sigma\tau_i^2 = 5.13$ and $s = 0.83$ dB), three replicates ($n = 3$) were required to test the inner duct diameter effect with $a = 5$ treatment groups (0, 6, 8, 12, and 16 inch) with sufficient power ($\beta \leq 0.20$) (Montgomery, 2001). The fifteen runs were randomized to prevent any bias from order or time.

## Study II Results

The results by frequency region for all the inner duct diameter are displayed in Figure 6. The $IL_{max}$ values in decibels for the two dependent variables (low and high frequency) are plotted against the independent variable of inner duct diameter in inches. The open boxes represent the low frequency data, and the closed triangles represent the high frequency data. Linear regression lines were added to the figure to help visualize the data.

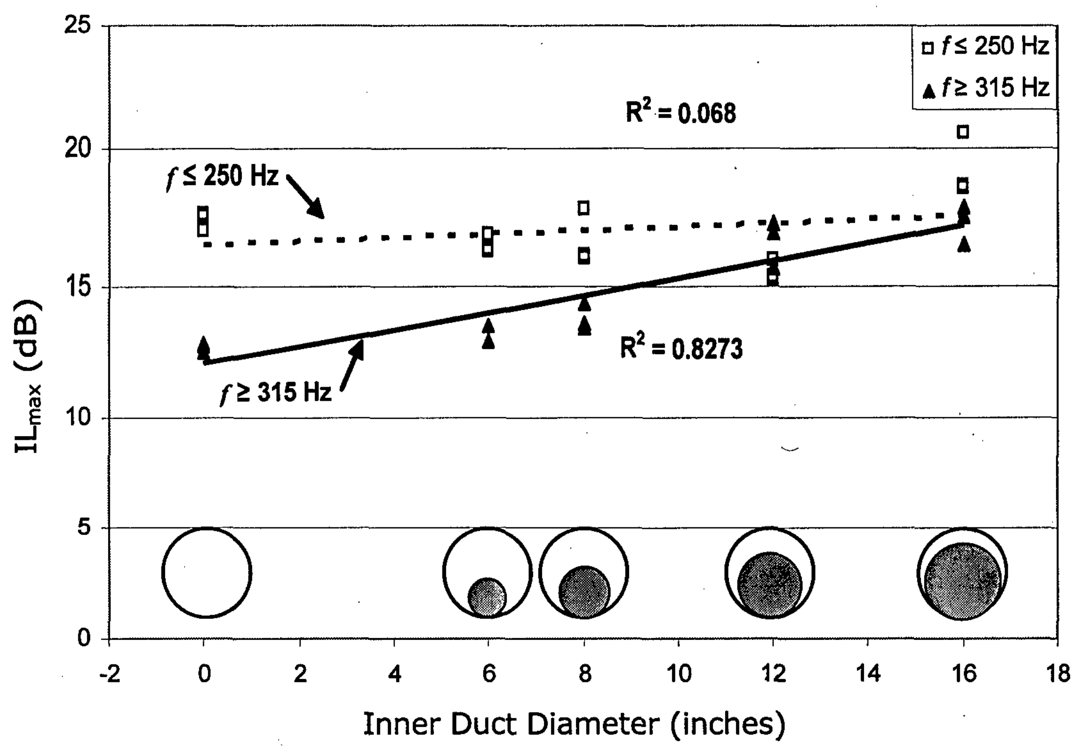


Figure 6. Study II Results, ILmax by inner duct diameter

Low Frequency: For the low frequency data, the best fit line does not describe the data well, with an associated $R^2$ of only 0.068. It appears that the independent variable does not have an effect on the low frequency $IL_{max}$ result. In other words, a constant value explains the data well, as was expected.

The treatment levels appeared to have unequal variances, so the O'Brien's test was conducted on the group variances to determine whether they were sufficiently equal (homoscedasticity). The O'Brien test returned a p-value of 0.4002 for the low frequency data set, indicating homoscedasticity, but observation of the data in Figure 6 still indicated possible heteroscedasticity. Also, Levene's test returned p=0.0195, indicating heteroscedasticity. Thus, although the data appear to have unequal variances, they may be considered homoscedastic. ANOVA tests on the data returned p=0.0012 for the low frequency data. Further, the model accounted for 81% of the sums of squares variability for the low frequency data. In case of actual heteroscedasticity, Welch's ANOVA (Welch, 1951; Brown and Forsythe, 1974, 1974a) was also run on the data to confirm the normal ANOVA results. Welch's ANOVA returned p=0.0157 for the low frequency data. The null hypothesis was rejected at $\alpha = 0.05$ for the low frequency data. There was an effect from the diameter on $IL_{max}$.

High Frequency: The high frequency data were certainly affected by the inner duct diameter. As the diameter increased and the open crescent-shaped air space in the outer 18 inch duct decreased, the cut-on frequency of the first higher order mode increased, so that the overall $IL_{max}$ at the higher frequencies should increase as well. That was reflected in the data in Figure 6. A linear regression line fit to the high frequency data had an $R^2$ of 0.8273 and did describe the data relationship somewhat.

Both the O'Brien and Levene tests for equality of variances on the high frequency data returned acceptable p-values of 0.5447 and 0.1001, respectively. The ANOVA returned $p<0.0001$ for the high frequency data. Further, the model accounted for 94% of the sums of squares variability for the high frequency data. In case of inequality of variances, Welch's ANOVA was run for comparison and returned p=0.0020 for the high frequency data, which agreed with the normal ANOVA results.

Low Frequency Multiple Comparisons: While this analysis concluded that the model was a good description of the data and that the inner diameter was important, the more important question was whether the different treatments were different from the open duct (zero inch inner diameter). The cell means and groups using the Tukey-Kramer Honestly Significant Difference (HSD) multiple comparison technique are listed in Table 2 for the low frequency data.

Table 2. Study II Results, Multiple comparison groups of inner duct diameter treatment means for low frequency ANC insertion loss data

| Inner Diameter (inch) | 0 | 6 | 8 | 12 | 16 |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| Mean IL (dB) | 17.4 | 16.5 | 16.6 | 15.6 | 19.2 |
| Group A* | x | | | | x |
| Group B* | x | x | x | x | |

*A = all treatments with similar means
*B = all treatments with similar means

The ANC insertion loss performances of the system with inner duct diameters of 0, 6, 8, and 12 inches were not significantly different from one another (group B). Also, while the 16 inch inner duct diameter system was different from the 6, 8, and 12 inch systems, it was not statistically different from the control treatment of zero inch (group A). These results indicated that for the low frequency region (20-250 Hz), there was no significant advantage to inserting inner ducts for cross-sectional partitioning inside the 18 inch outer duct. A visual inspection of the data points with the confidence intervals of the treatment means shown as error bars supported the statistical conclusions (Figure 7).

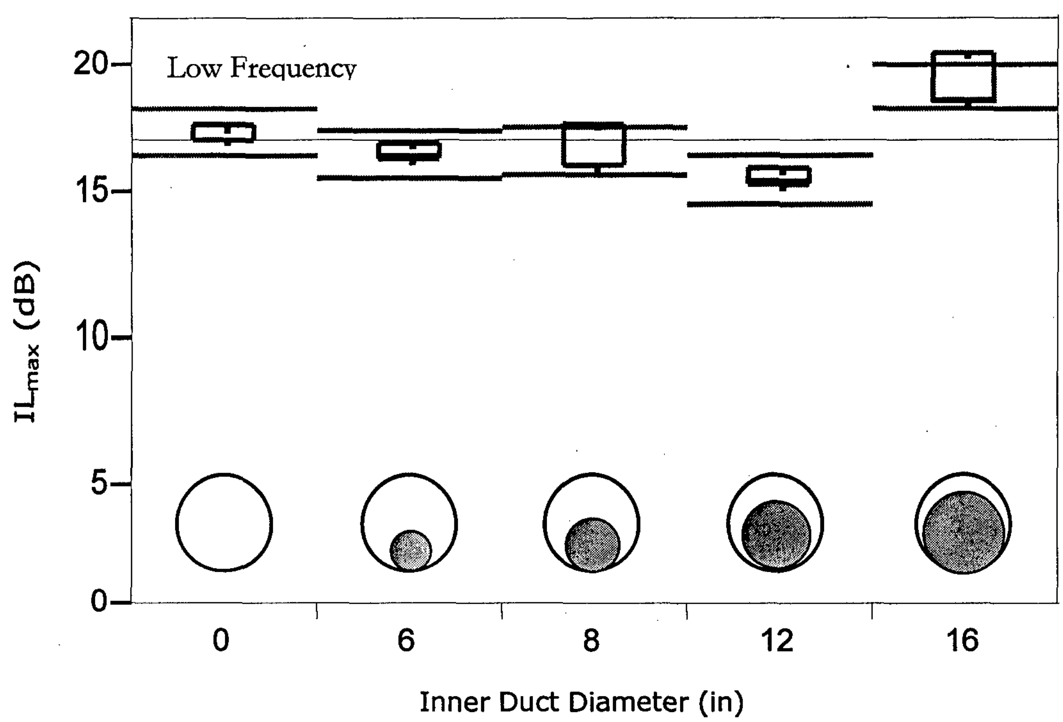


Figure 7. Study II Results, Low frequency inner duct diameter data treatment means comparisons with sketches of treatment conditions

High Frequency Multiple Comparisons: For the high frequency data, the analysis concluded that the model was a good description of the data and that the inner diameter was also important, but the more important question was still whether the different treatments were different from the open duct (zero inch inner diameter). The cell means and groups using the Tukey-Kramer Honestly Significant Difference (HSD) multiple comparison technique are listed in Table 3 for the high frequency data.

Table 3. Study II Results, Multiple comparison groups of inner duct diameter treatment means for high frequency ANC insertion loss data

| Inner Diameter (inch) | 0 | 6 | 8 | 12 | 16 |
|---|---|---|---|---|---|
| Mean IL (dB) | 12.9 | 13.4 | 13.9 | 16.6 | 17.3 |
| Group A* | | | | x | x |
| Group B* | x | x | x | | |

*A = all treatments with similar means
*B = all treatments with similar means

The ANC insertion loss performances of the system with inner duct diameters of 0, 6, and 8 inches were not significantly different from one another (group B). The ANC insertion loss of the 12 and 16 inch diameter inner ducts was significantly higher than the other conditions (group A). These results indicated that for the high frequency region (315-5k Hz), there was no significant advantage to inserting 6 or 8 inch diameter inner ducts for cross-sectional partitioning inside the 18 inch outer duct. However, inserting 12 or 16 inch diameter inner ducts resulted in an average 3.7 - 4.4 dB increase in ANC insertion loss above the 18 inch diameter duct alone.

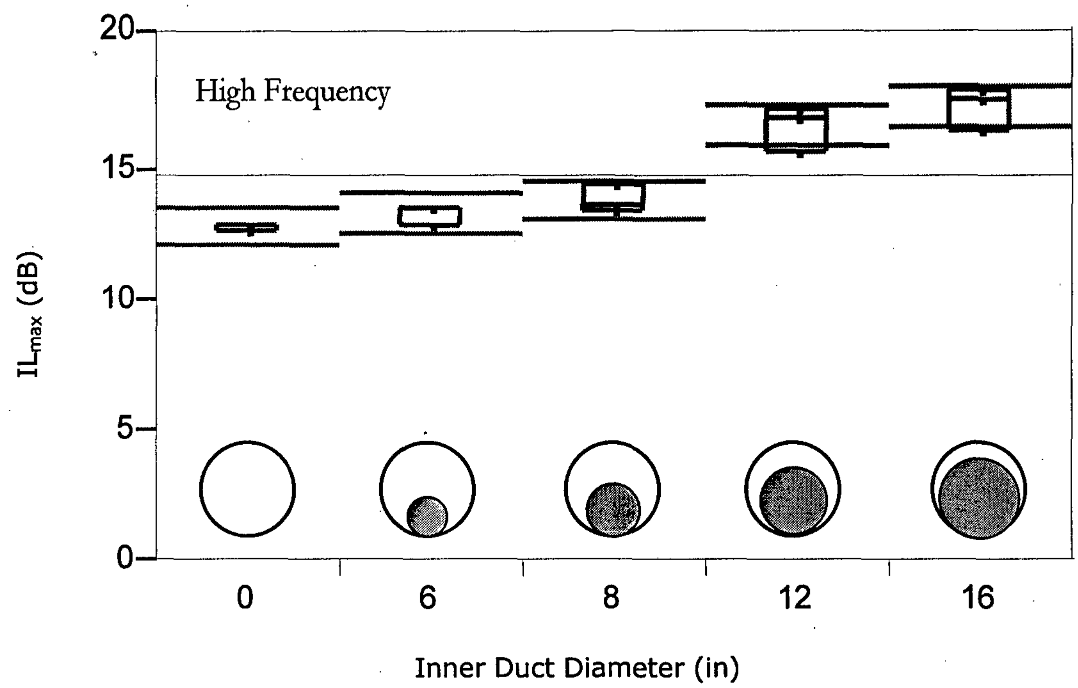


Figure 8. Study II Results, High frequency inner duct diameter data treatment means comparisons with sketches of treatment conditions

A visual inspection of the data points with the confidence intervals of the treatment means drawn in as error bars (Figure 8) supported the statistical conclusions that the 12 and 16 inch diameter inner duct treatments resulted in higher ANC insertion loss than the other treatments.

## Study II Discussion

The purpose of this two duct study (Study II) was to determine whether there was a significant effect on ANC insertion loss from the size of the remaining crescent-shaped space inside the 18 inch diameter outer duct when inner ducts of diameters 6, 8, 12, and 16 inches were inserted as cross-sectional partitions. The inner duct diameter stage of the study indicated that ANC insertion loss in the low frequency region was not significantly affected by inner duct diameter. However, there was a significant increase in ANC insertion loss at higher frequencies when the inner duct diameters were large enough.

### Study II Conclusion

The results of the inner diameter study indicated that it would be prudent to test only the 12 and 16 inch diameter inner ducts for Study III. However, since there was very little open space inside the 18 inch outer duct with the 16 inch inner duct inserted so that it may be impractical to implement, the 12 inch inner diameter duct was selected for Study III.

## STUDY III – SIMULTANEOUS DUAL-DUCT OPERATION

The logical progression in the overall research to examine the effects of cross-sectional partitioning on ANC insertion loss was to make both inner and outer ducts "live" by having ANC activated for both simultaneously. There were two stages to the third study; first to run two independent full ANC systems on the two ducts, then to see if the amount of hardware could be reduced on one of the ANC duct systems to reduce costs. In both stages, the cross-sectional partitioned treatment was compared to ANC within the 18 inch outer duct alone.

### Study III Unique Apparatus

Study III used the previously described 18 inch outer duct, with a 12 inch inner duct inserted. Based on the preliminary finding that coaxial was no better than the more convenient tangent placement, a 12 inch inner diameter duct was placed tangent to the bottom of the 18 inch outer duct. The inner duct was open to the same source noise and had a separate reference microphone, control speaker, and error microphone (see Figure 9). The 12 inch ANC was run by a separate set of channels on the same active noise controller as the 18 inch outer duct. A 4 inch diameter, 8 inch long piece of duct connected the control speaker to the 12 inch duct through the wall of the 18 inch duct. The control speaker for the 12 inch system was isolated inside a 3.4 $ft^3$ plywood box to reduce cross-contamination of noise between the two ducts (see Figure 10). The gaps between the plywood box and the 4 inch diameter control speaker tube, as well as the 18 inch outer duct wall and the 4 inch tube, were packed with acoustic foam and sealed with duct tape to reduce noise cross-contamination.

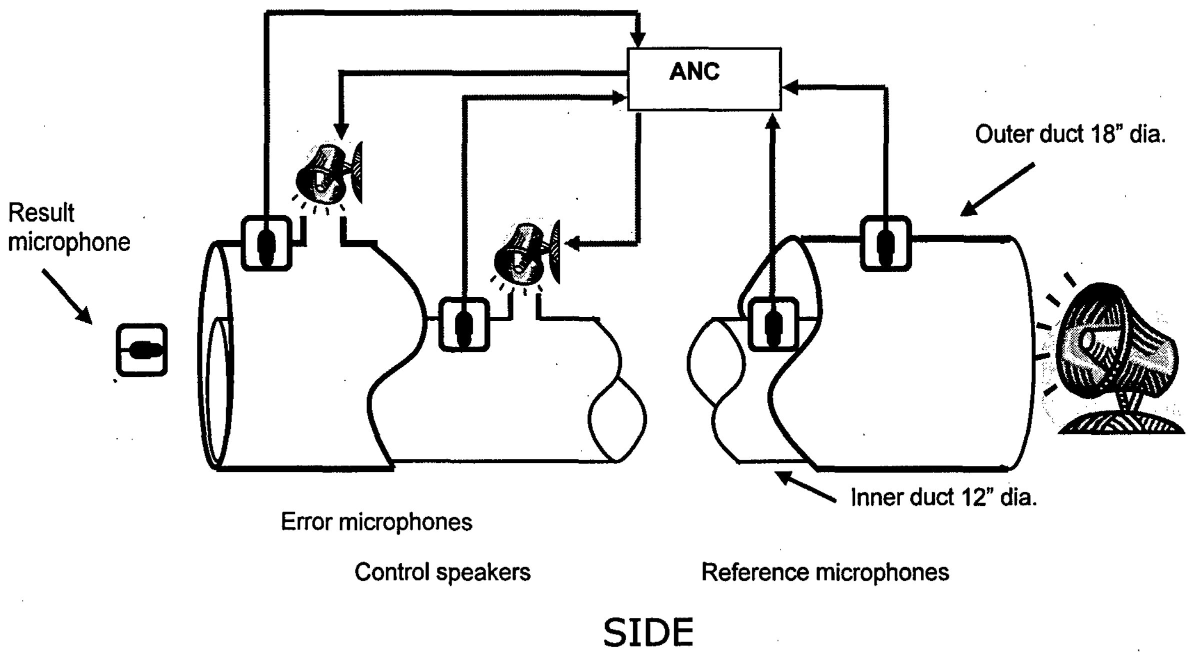


Figure 9. Study III Apparatus, Side view

In order to compare the difference in overall ANC insertion loss with and without the inner duct system in place, a separate result microphone was placed at the center of the end of the 18 inch duct, 4 inches past the end (see Figure 9). Both stages of the study compared a simultaneous dual-duct system to a single 18 inch duct system, as in Figure 10.

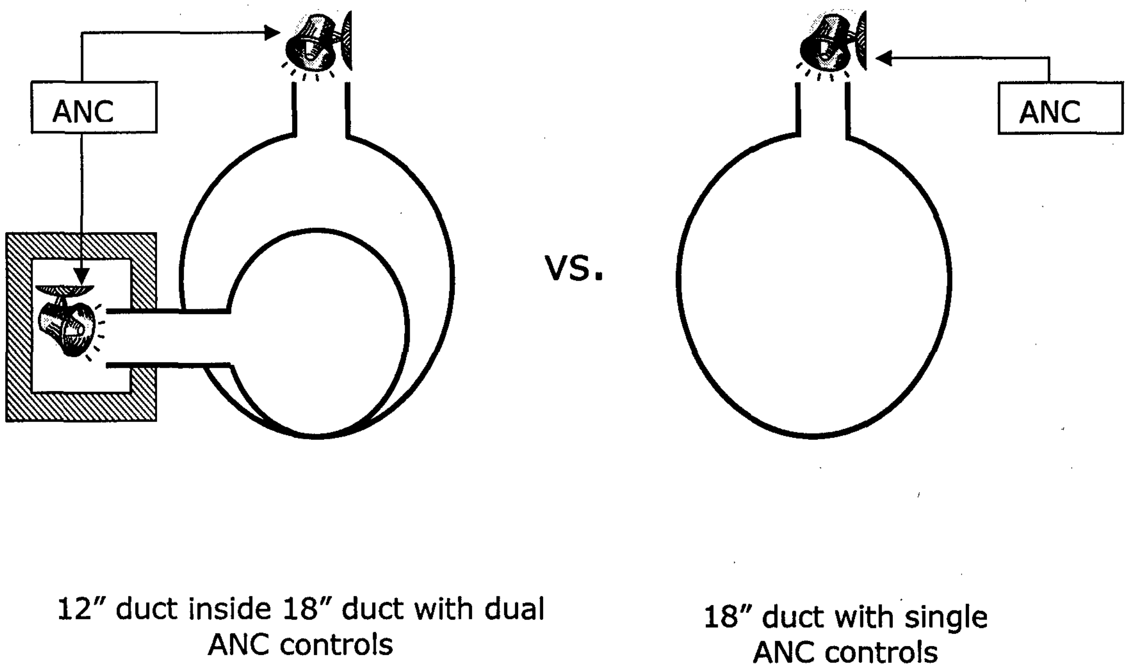


Figure 7. Study III Apparatus, end view of apparatus with control speakers

The second stage of the study (Study IIIb) was to determine whether a reduced hardware system could still return better ANC insertion loss than the 18 inch duct ANC alone. Preliminary studies attempted to eliminate hardware and check the stability of the system. When an error microphone from either the 18 inch or 12 inch system was removed, the system became too unstable to measure within seconds and had to be shut down to protect the speakers. When a single control speaker signal was sent to each control speaker, there was no measurable ANC insertion loss for either system. The only viable hardware reduction scheme was determined to be eliminating the reference microphone from the 18 inch outer duct system and feeding the 12 inch inner duct reference microphone signal to the outer duct control channels and algorithm.

## Study IIIa: Simultaneous Dual-duct Operation

### Study IIIa Model and Study Design

Study IIIa was designed to test the hypothesis that there was no difference in $IL_{max}$ between employing one and two channels for controls. For the latter, one channel controlled the inner duct and the second controlled the gap between the two ducts. The statistical model for this simple comparative experiment was:

$$IL_{ij} = \mu_i + \varepsilon_{ij}$$

Where:

$IL_{ij}$ = insertion loss in decibels (dB)
$\mu_i$ = average insertion loss at the $i^{th}$ factor level, $i = 1, 2, \ldots, a$
$\varepsilon_{ij}$ = random error, $j = 1, 2, \ldots, n$

This model was used to test the following hypothesis on the comparison of the two treatments:

$H_0$: $\mu_1 = \mu_2$

$H_1$: $\mu_1 \neq \mu_2$

Stated non-mathematically, the hypothesis was:

$H_0$: No difference between the 18 inch duct system alone and the dual duct system operated simultaneously
$H_1$: There is a difference

Power calculations indicated that, given the average variability in the preliminary tests ($s$ = 1.72 dB) and the desired detectable difference ($\delta$ = 1.5 dB), four replicates (n = 4) were required to compare the means with $a$ = 2 treatment groups (single vs. dual) with sufficient power ($\beta \leq 0.20$) (Montgomery, 2001). The eight runs were randomized to prevent any bias from order or time.

### Study IIIa Results

As with previous results, significant differences were found for the higher but not the lower frequency range.

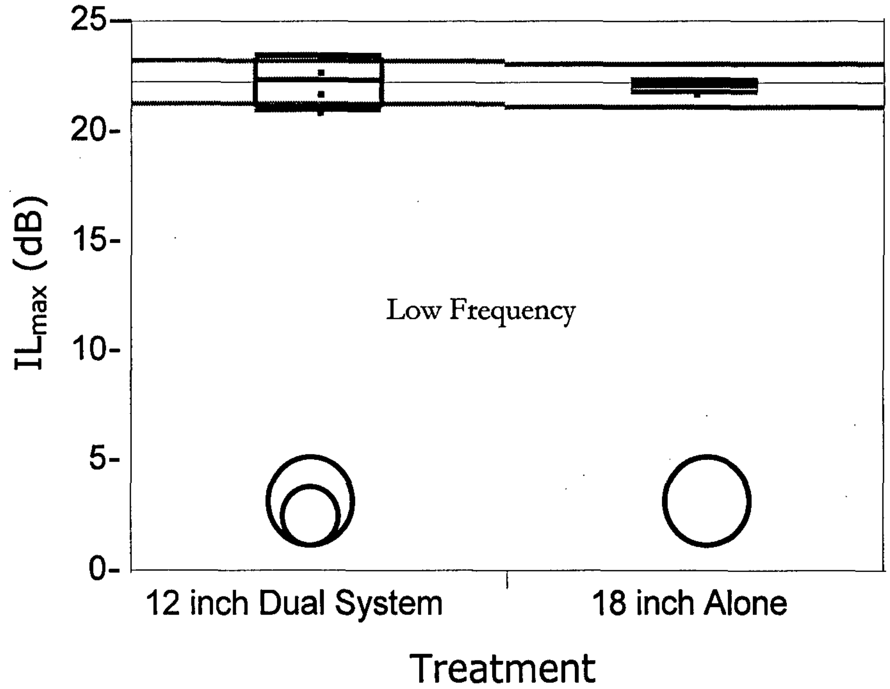


Figure 8. Study IIIa Results, Low frequency comparison of $IL_{max}$ by treatment (Dual 12 inch full hardware system vs. 18 inch single system)

Low Frequency: The results for the low frequency $IL_{max}$ comparison between the dual system and the single 18 inch system are displayed in Figure 11. An unequal variance t-test indicated that the two treatment groups were not significantly different (p=0.3749). The graph of the data supported that result, as the variances were very different and the $IL_{max}$ values for the two groups overlap.

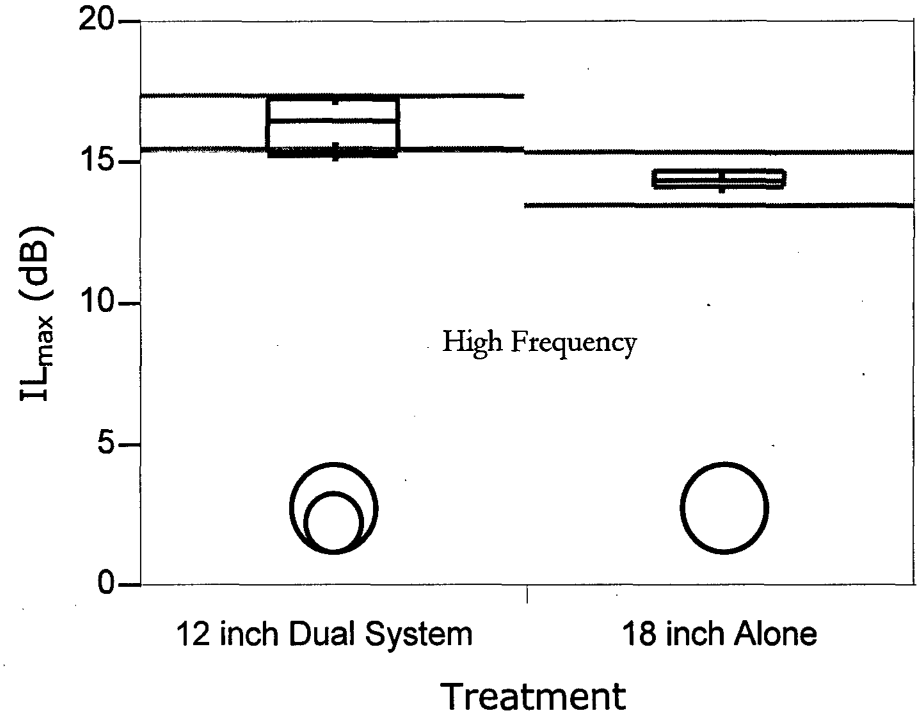


Figure 9. Study IIIa Results, High frequency comparison of $IL_{max}$ by treatment (Dual 12 inch full hardware system vs. 18 inch single system)

High Frequency: The results for the high frequency $IL_{max}$ comparison between the dual system and the single 18 inch system are displayed in Figure 12. The data appear to show both different means and strikingly different variances. An unequal variance t-test indicated that the two treatment groups were significantly different ($p=0.0178$). The graph of the data supported that result, as the variances were very different but the $IL_{max}$ values for the two groups did not overlap anywhere in their ranges.

### Study IIIa Discussion

The dual system achieved 2 dB better ANC insertion loss over the 18 inch single system on average. While that difference is significant, it is not highly substantial. However, when the 1/3 octave band insertion loss values were plotted in Figure 13, there was a substantial difference between the two treatment groups for certain high frequency third octave bands. The dual system data points were denoted by "+" signs, and the 18 inch single system data points were denoted by open squares. The vertical line in the center of the figure marks the division between low and high frequency for the experiments. The mean difference between the groups at the 315 Hz band is 4 dB. The effect is obscured somewhat from the decibel summation in the $IL_{max}$ result because the 18 inch single system had a slightly higher average insertion loss at the 400 Hz band. The 4 dB difference in means in this narrow range is of practical importance only if that frequency range is prominent in the source to be controlled.

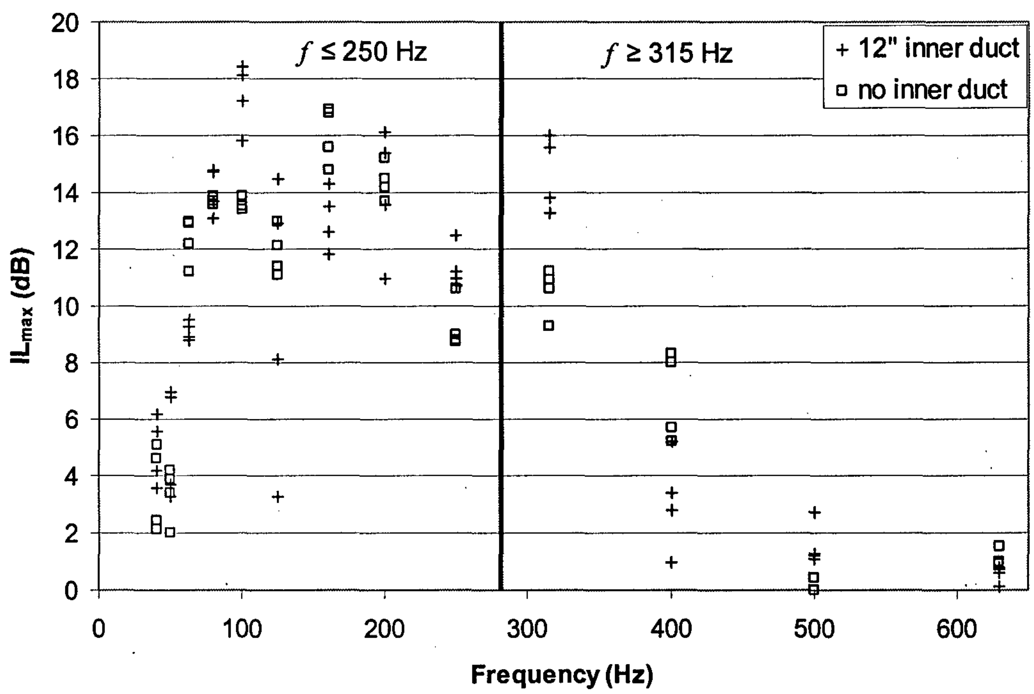


Figure 10. Study IIIa Results, ANC insertion loss by 1/3 octave bands (Dual 12 inch full hardware system vs. 18 inch single system)

### Study IIIa Conclusion

The dual system achieved 2 dB better ANC insertion loss over the 18 inch single system on average. While that difference is significant, it is not highly substantial unless the individual 315 Hz third octave band is considered. This design may still be a viable option for some noise control strategies, depending on the frequency spectrum of the noise to be controlled. The second stage of the simultaneous dual-duct study (IIIb) was intended to increase the attractiveness of the strategy by reducing the hardware costs of the dual-duct system.

### Study IIIb: Simultaneous Dual-duct Operation with Reduced Hardware

While Study IIIa confirmed the efficacy of the simultaneously-operated dual-duct system (using another round duct for the cross-sectional partitioning), it may be useful to reduce the hardware of the system components to decrease the cost of the intervention. As described in the unique apparatus section of this chapter, several hardware reduction schemes were attempted, but only one provided the ANC stability needed to conduct comparative experiments. The only reduced hardware option for the dual-duct system was to use the reference microphone inside the 12 inch diameter inner duct as the reference signal for both duct systems. Each duct (18 inch outer and 12 inch inner ducts) had separate ANC controller channels and separate control speaker signals and error microphones. Other than the single reference signal, the two systems were independent, but operating simultaneously.

#### Study IIIb Model and Study Design

Study IIIb was designed to test the hypothesis that there was no difference in $IL_{max}$ between the 18 inch ANC system alone and the dual ANC system with reduced hardware. The statistical model for this simple comparative experiment was:

$$IL_{ij} = \mu_i + \varepsilon_{ij}$$

Where:

$IL_{ij}$ = insertion loss in decibels (dB)
$\mu_i$ = average insertion loss at the $i^{th}$ factor level, $i = 1, 2, \ldots, a$
$\varepsilon_{ij}$ = random error, $j = 1, 2, \ldots, n$

This model was used to test the following hypothesis on the comparison of the two treatments:

$$H_0: \mu_1 = \mu_2$$

$H_1$: $\mu_1 \neq \mu_2$

Stated non-mathematically, the hypothesis was:

$H_0$: No difference between the 18 inch duct system alone and the dual duct system operated simultaneously with reduced hardware
$H_1$: There is a difference

Power calculations indicated that, given the average variability in the preliminary tests ($s$ = 1.72 dB) and the desired detectable difference ($\delta$ = 2.0 dB), three replicates (n = 3) were required to compare the means with $a$ = 2 treatment groups (single vs. dual with reduced hardware) with sufficient power ($\beta \leq$ 0.20) (Montgomery, 2001). The six runs were randomized to prevent any bias from order or time.

### Study IIIb Results

Differing from previous results, significant differences were found for both the higher and the lower frequency range.

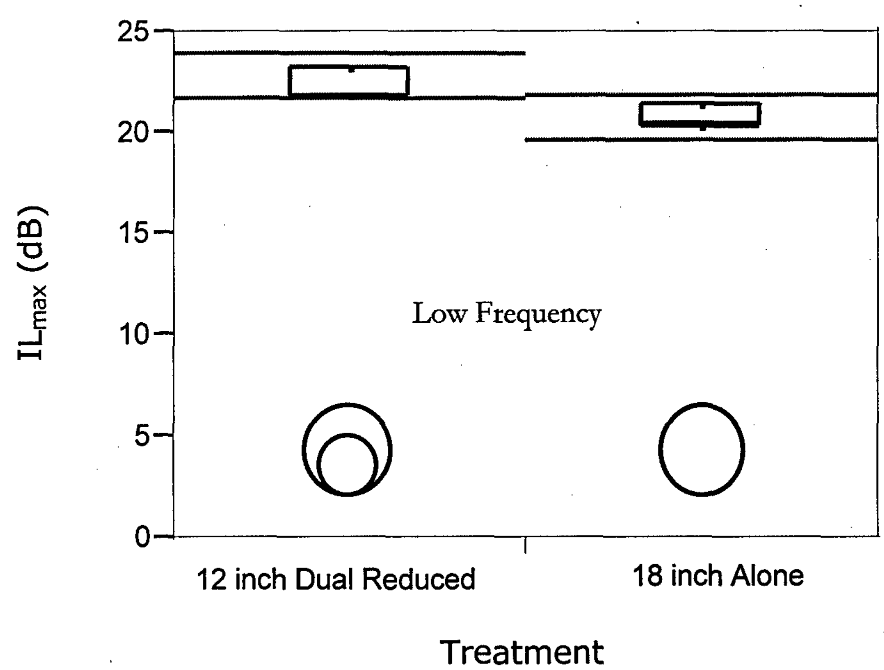


Figure 11. Study IIIb Results, Low frequency comparison of $IL_{max}$ by treatment (Dual 12 inch reduced hardware system vs. 18 inch single system)

Low Frequency: The results for the low frequency $IL_{max}$ comparison between the reduced hardware dual system and the single 18 inch system are displayed in Figure 14. The means appear different, but the variances appear similar. An F-test on the equality of variances indicated that the variances were not significantly different (p=0.3848). An equal variance t-test indicated that the two treatment groups were significantly different (p=0.0146). The graph of the data supported that result. Although the variances are not very different, the $IL_{max}$ values for the two groups do not overlap. At low frequency, the dual reduced system achieved 2 dB more ANC insertion loss on average.

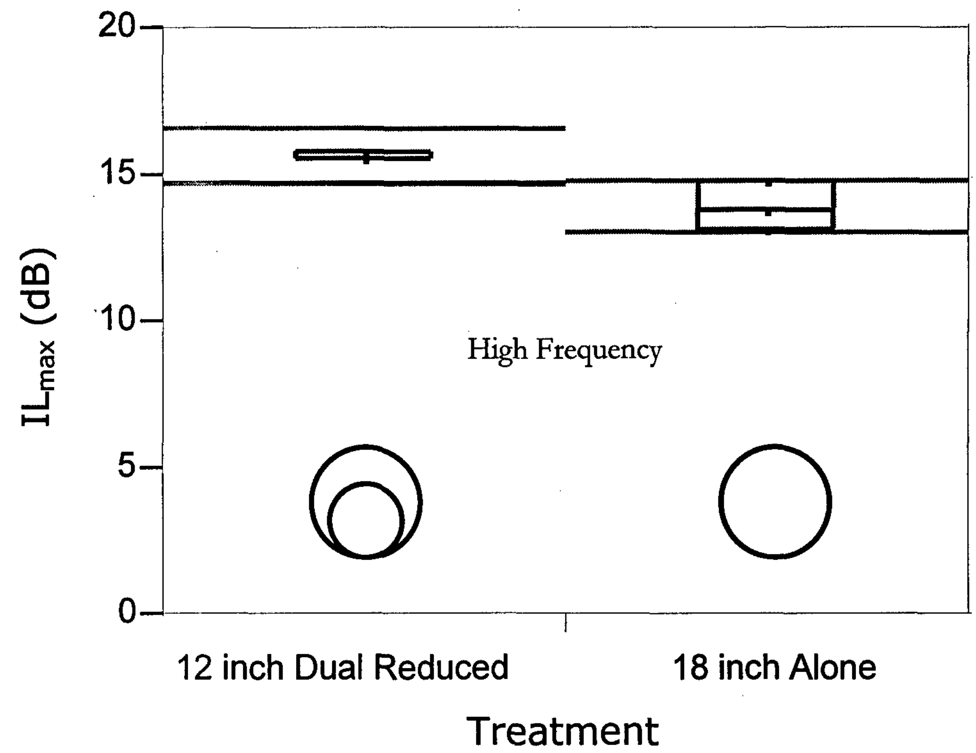


Figure 12. Study IIIb Results, High frequency comparison of $IL_{max}$ by treatment (Dual 12 inch reduced hardware system vs. 18 inch single system)

High Frequency: The results for the high frequency $IL_{max}$ comparison between the reduced hardware dual system and the single 18 inch system are displayed in Figure 15. The variances and the means of the data appear different. An F-test on the equality of variances indicated that the variances were significantly different ($p=0.0257$). An unequal variance t-test indicated that the two treatment groups were significantly different ($p=0.0333$). The graph of the data support that result, since the variances are very different but the $IL_{max}$ values for the two groups do not overlap. At high frequency, the dual system achieved 1.7 dB more ANC insertion loss on average.

### Study IIIb Discussion

The dual system with reduced hardware achieved 1.7 to 2 dB better ANC insertion loss over the 18 inch single system on average. While that difference was significant, it was not at all substantial. Further investigation of the 1/3 octave band insertion loss values (Figure 16) revealed that there was not the substantial difference between the two treatment groups for high frequency third octave bands that there was for the full hardware dual system in Study IIIa. The dual system data points were denoted by "+" signs, and the 18 inch single system data points were denoted by open squares. The vertical line in the center of the figure marks the division between low and high frequency for the experiments. The mean difference between the groups at the 315 Hz band is 2 dB. In effect, the summary high and low frequency $IL_{max}$ values used in the comparison did not seem to obscure the underlying data. Although the difference in $IL_{max}$ for high and low frequency between the two treatments was significant, it was not substantial, even at individual 1/3 octave bands.

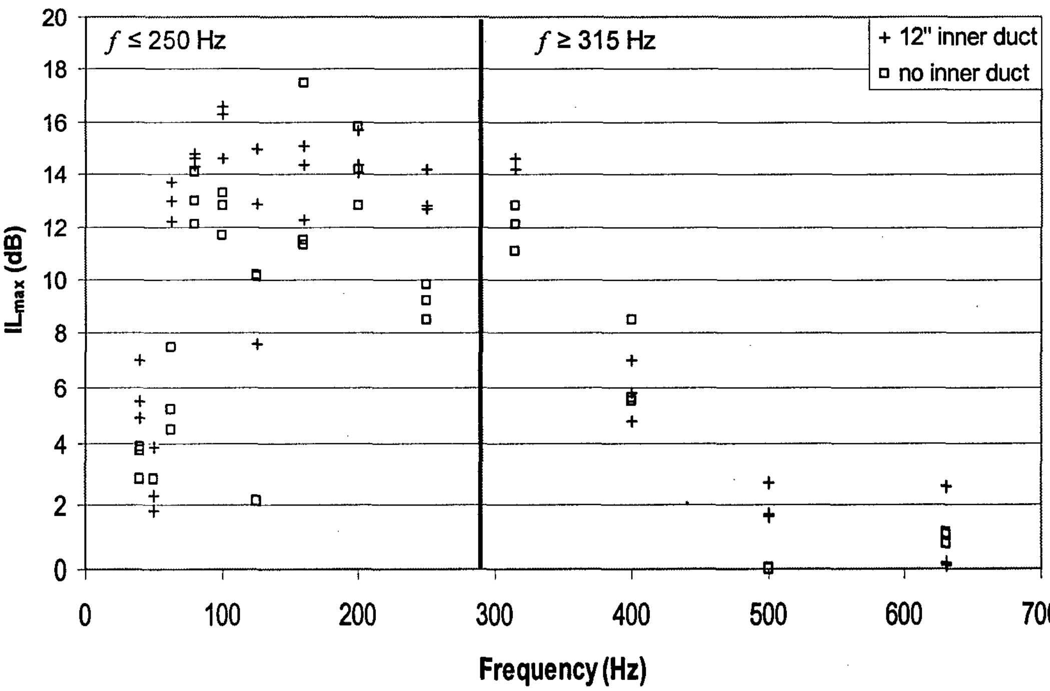


Figure 13. Study IIIb Results, ANC insertion loss by 1/3 octave bands (Dual 12 inch reduced hardware system vs. 18 inch single system)

### Study IIIb Conclusion

The dual system with reduced hardware was significantly better, but not substantially better, than the 18 inch single system on average for both low and high frequency ranges. This design may still be a viable option for some noise control strategies, but only if the needed additional insertion loss were very small. The results indicated that a reduced hardware dual-duct cross-sectional partitioning system could increase the high and low frequency ANC insertion loss on a large 18 inch outer duct. It is also important to keep in mind that the average ANC insertion loss for the reduced hardware dual duct system was 15.7 dB for high frequency and 22.8 dB for low frequency. Such insertion loss values are substantial with regards to noise control.

## STUDY IV – CROSS-SHAPED SPLITTER

Partitioning with an inner duct was a marginal success. However, it is possible that dividing an 18 inch duct into quadrants would be more successful since the maximum free dimension would be much less. The fourth study was designed to test the ANC insertion loss in the 18 inch duct using the cross-shaped partition compared to ANC within the 18 inch outer duct alone.

### Study IV Unique Apparatus

Study IV used the previously described 18 inch diameter outer duct, with a 24 ft long cross-shaped plywood splitter inserted into the 18 inch duct. The 18 inch diameter duct was modified in that the control speakers at the tee area were mounted directly on the side wall for Study IV. Four control speakers were mounted at the 18 inch diameter tee at 21 ft from the source speaker. Several preliminary tests kept all four quadrants live with separate ANC channels devoted to the individual quadrants. Although the cross-splitter was caulked at its center to reduce noise cross-contamination between quadrants, the ANC system was too unstable to have all four channels operating, most likely due to mutual interference. Even though the quadrants should have similar shape and noise traveling down their lengths, the single ANC controller could not adequately control the four individual quadrants. Therefore, the study was restricted to compare a single quadrant, with the other three quadrants blocked off, vs. the 18 inch diameter duct alone, as in Figure 17. The other three quadrants were blocked with a dense rubber sheet across the face sealed with duct tape, and acoustic foam stuffed inside the duct.

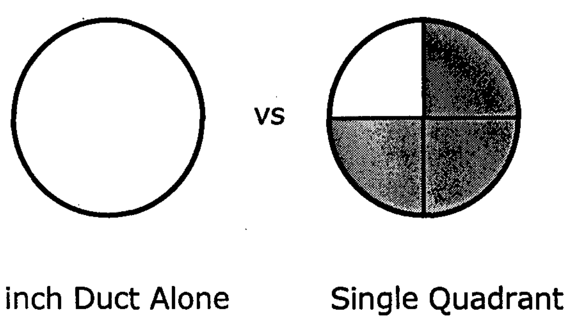


Figure 14. Study IV Apparatus, End view of comparison treatments

Since not all quadrants had "live" ANC systems in place, an external result microphone would not represent the two treatments. Instead, the comparisons used the error microphone signal, which was mounted at the same position for both treatments, 23 ft along the duct.

### Study IV Model and Study Design

Study IV was designed to test the hypothesis that there was no difference in $IL_{max}$ between the 18 inch ANC system alone and the single quadrant ANC system. The statistical model for this simple comparative experiment was:

$$IL_{ij} = \mu_i + \varepsilon_{ij}$$

Where:

$IL_{ij}$ = insertion loss in decibels (dB)
$\mu_i$ = average insertion loss at the $i^{th}$ factor level, $i = 1, 2, \ldots, a$
$\varepsilon_{ij}$ = random error, $j = 1, 2, \ldots, n$

This model was used to test the following hypothesis on the comparison of the two treatments:

$$H_0\colon \mu_1 = \mu_2$$

$$H_1\colon \mu_1 \neq \mu_2$$

Stated non-mathematically, the hypothesis was:

$H_0$: No difference between the 18 inch duct system alone and the single quadrant system
$H_1$: There is a difference

Power calculations indicated that, given the average variability in the preliminary tests ($s$ = 0.81 dB) and the desired detectable difference ($\delta$ = 3 dB), three replicates (n = 3) were required to compare the means with $a$ = 2 treatment groups (18 inch vs. single quadrant) with sufficient power ($\beta \leq 0.20$) (Montgomery, 2001). The six runs were randomized to prevent any bias from order or time.

### Study IV Results

For this study, significant differences were found for both the higher and the lower frequency ranges. However, the partition was counter-productive for the low frequency range.

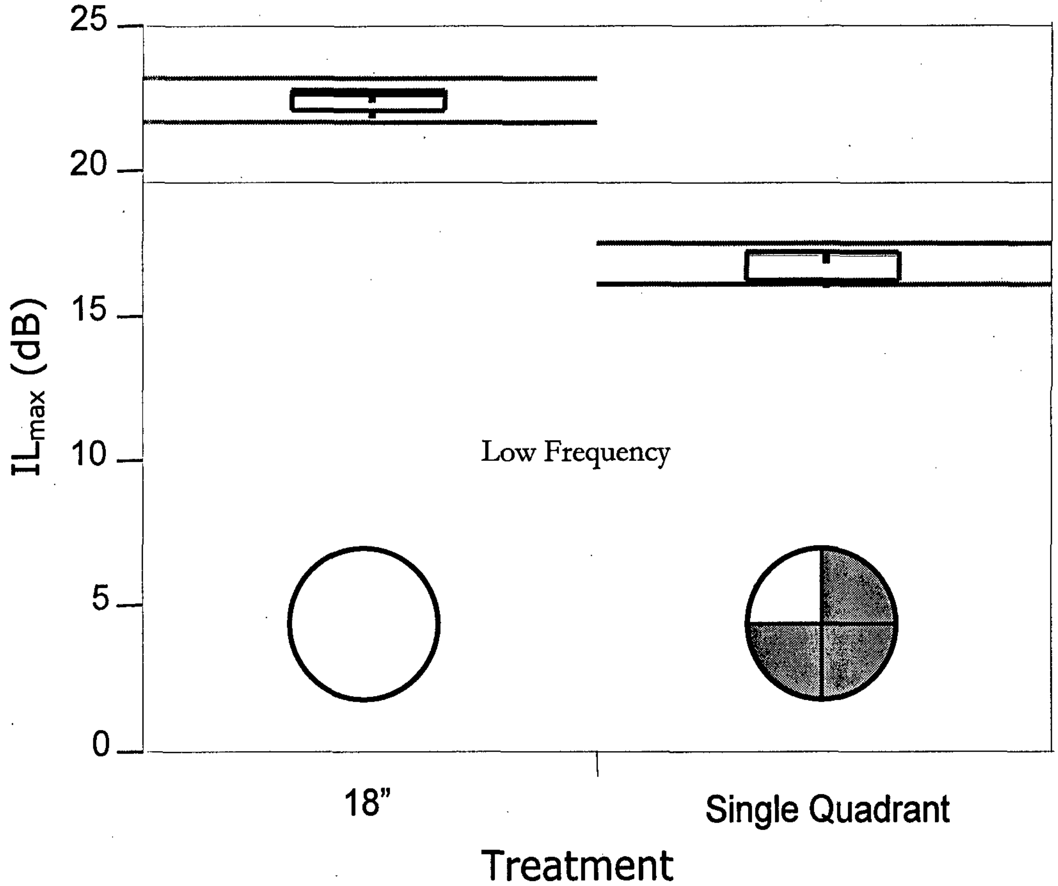


Figure 15. Study IV Results, Low frequency comparison of $IL_{max}$ by treatment (Single quadrant system vs. 18 inch duct system)

Low Frequency: The results for the low frequency $IL_{max}$ comparison between the single quadrant system and the 18 inch diameter duct system are displayed in Figure 18. The variances of the two groups did not appear different, but the means were very different. An F-test on the equality of variances indicated that the variances were not significantly different ($p=0.3055$). An equal variance t-test indicated that the two treatment groups were significantly different ($p<0.0001$). The graph of the data supported that result; the variances were not very different, and the $IL_{max}$ values for the two groups did not overlap. The single quadrant low frequency $IL_{max}$ values were 5.6 dB lower than the 18 inch diameter duct ANC system alone. The partition was counter-productive for the low frequency range.

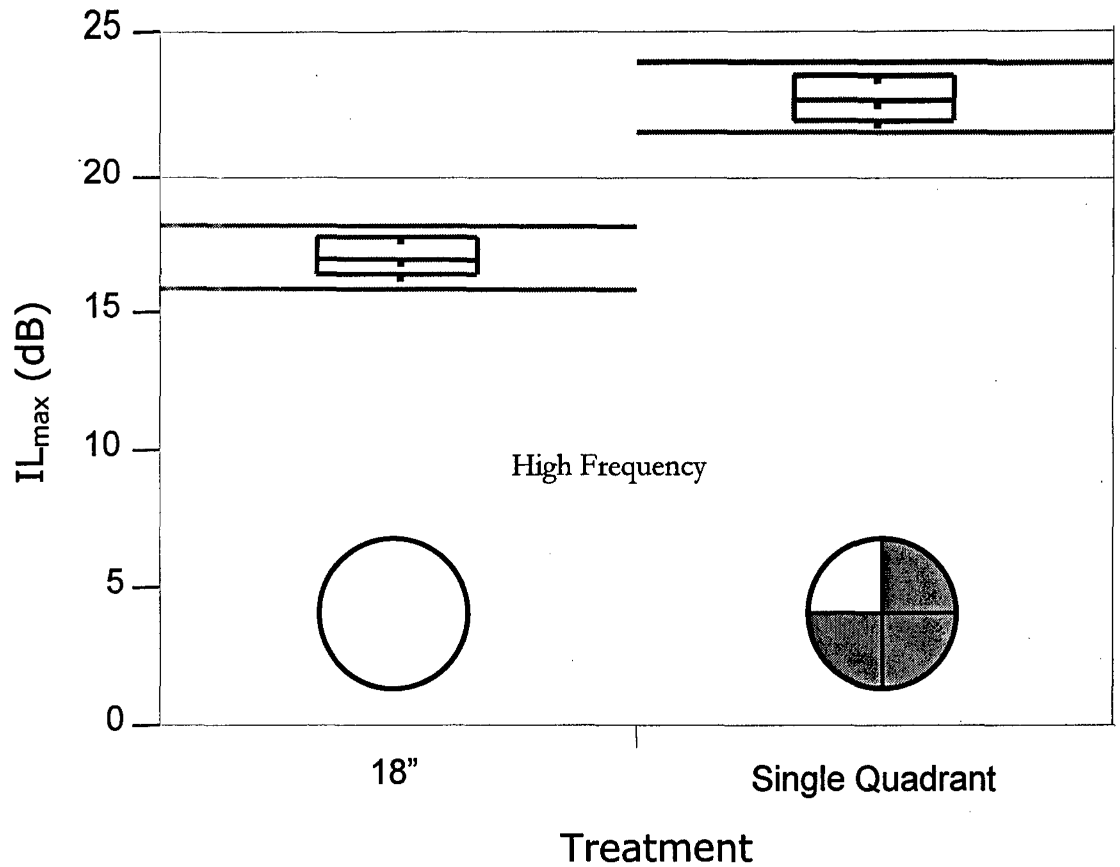


Figure 19. Study IV Results, High frequency comparison of $IL_{max}$ by treatment (Single quadrant system vs. 18 inch duct system)

High Frequency: The results for the high frequency $IL_{max}$ comparison between the single quadrant system and the 18 inch diameter duct system are displayed in Figure 19. The variances did not appear different, but the means did. An F-test on the equality of variances indicated that the variances were not significantly different (p=0.4905). An equal variance t-test indicated that the two treatment groups were significantly different (p=0.0003). The graph of the data supported that result; the variances did not appear very different, and the $IL_{max}$ values for the two groups did not overlap. The single quadrant low frequency $IL_{max}$ values were 5.8 dB higher than the 18 inch diameter duct ANC system alone, a substantial improvement.

## Study IV Discussion

The single quadrant system achieved 5.8 dB higher ANC insertion loss over the 18 inch diameter system on average at high frequency, but 5.6 dB lower ANC insertion loss at low frequency. The difference (in both directions) is both significant and substantial. The 1/3 octave band insertion loss values were plotted in Figure 20. The single quadrant system data points were denoted by "+" signs, and the 18 inch diameter duct system data points were denoted by open squares. The vertical line in the center of the figure marks the division between low and high frequency for the experiments. The mean difference between the groups at the 630 Hz band is 15.5 dB (17.8 dB for the single quadrant vs. 2.3 dB for the 18 inch duct system). Although some low frequency ANC insertion loss would be sacrificed by the cross-shaped splitter, the increase in high frequency ANC insertion loss would be quite substantial. Further, the high frequency ANC insertion loss for the single quadrant treatment extended out to 1000 Hz (8.1 dB), which would help fill the frequency gap between passive and active noise control.

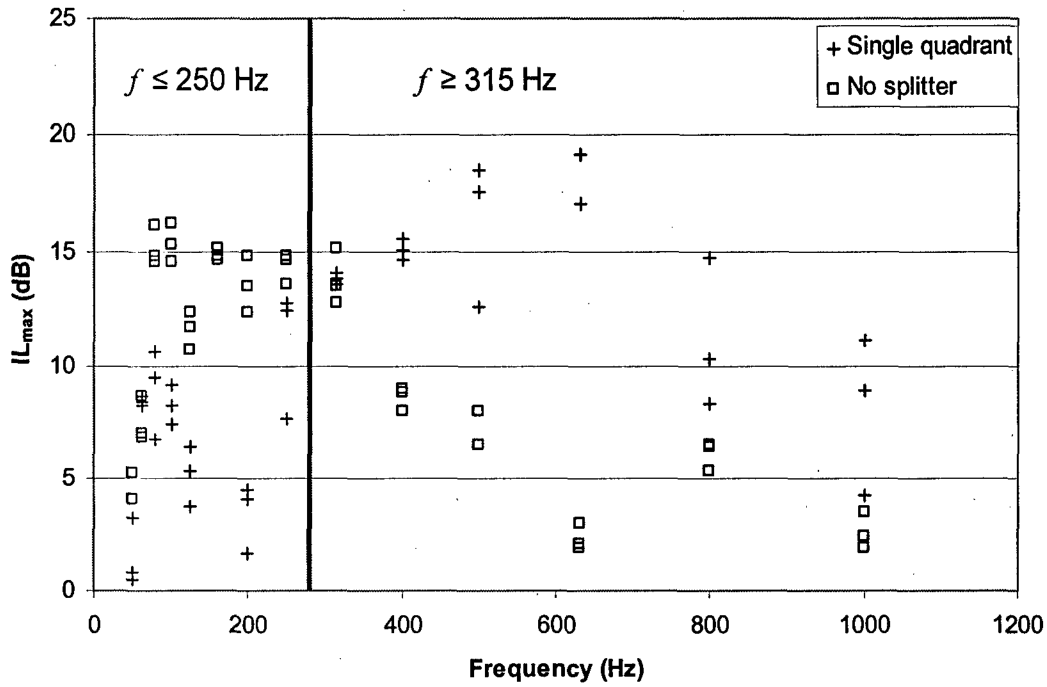


Figure 16. Study IV Results, ANC insertion loss by 1/3 octave bands (Single quadrant system vs. 18 inch duct system)

## Study IV Conclusion

While the ANC controller was not capable of having all four quadrants active at once, the single quadrant experiment of Study IV was very interesting. The average ANC insertion loss for the single quadrant system at 630 Hz was 17.8 dB. If all four quadrants could be operated with a more advanced ANC controller, perhaps a cross-shaped cross-sectional partitioning of a large round duct would be the best design to extend active control of noise into the higher frequency regions. However, the loss of low frequency control would have to be considered.

The lower $IL_{max}$ at the low frequency regions for the single quadrant design may well have to do with the error microphone positioning. Less than 5 dB of insertion loss was achieved in the single quadrant at the 200 Hz 1/3 octave band. The error microphone position relative to the duct and the control speaker may have been such that the ANC was less effective for low frequency, longer wavelength range. This same problem may be less important for the higher frequency, shorter wavelength range. This could explain some of the Study IV results.

# DISCUSSION

The p-values and summary results from all of the studies are displayed in Table 4.

Table 4. p-values and summary results from all studies to describe independent variables

| Study | Variable | $H_0$ | Test | p-values and $IL_{max}$ difference Low Frequency | High Frequency |
|---|---|---|---|---|---|
| II | Inner duct diameter | No effect of inner duct diameter | 1-way ANOVA | p=0.0157 (no effect) | p=0.0020 (3.7-4.4 dB) |
| IIIa | Simultaneous operation | No difference between 18" duct alone and dual-duct simultaneously | t-test | p=0.3749 (no effect) | p=0.0178 (2 dB) |
| IIIb | Hardware combination | No difference between 18" duct alone and dual-duct with single reference microphone | t-test | p=0.0146 (2 dB) | p=0.0333 (1.8 dB) |
| IV | Cross-shaped splitter | No difference between 18" duct alone and single quadrant area | t-test | p<0.0001 (-5.6 dB) | p=0.0003 (5.8 dB) |

*Equality of variances assumption may have been violated for two-way ANOVA for interaction p-value

Studies II and III investigated the cross-sectional partitioning method of inserting a smaller round duct inside a larger round duct. Study II showed that the inner duct diameter of a dual-duct system had an effect on both high and low frequency ANC insertion loss. However, follow-up multiple comparison tests showed that the several inner duct diameter treatments were not different from the large duct alone at low frequency. At high frequency, the 12 inch and 16 inch diameter inner duct treatments were significantly better than the 18 inch duct alone, with associated increase in $IL_{max}$ of 3.7 and 4.4 dB, respectively.

Study III was designed to actually operate the dual-duct system simultaneously and compare it to the 18 inch duct ANC system alone. Study IIIa used two separate ANC systems with complete hardware (speakers and microphones) vs. 18 inch diameter duct ANC system alone. There was no difference between the two systems at low frequency, but there was a modest 2 dB increase in $IL_{max}$ for the dual-duct system at high frequency. Study IIIb used a reduced hardware configuration with a single reference microphone for the dual duct system vs. the 18 inch diameter duct ANC system alone. There was a significant but modest increase in $IL_{max}$ using the reduced hardware dual-duct system for both low (2 dB) and high (1.8 dB) frequency.

Finally, Study IV explored the cross-shaped splitter for cross-sectional partitioning. The $IL_{max}$ of the single pie-shaped quadrant system was significantly different from the 18 inch diameter duct ANC system alone, but with mixed results. At low frequency, the splitter degraded performance by 5.6 dB but improved performance by 5.8 dB at high frequency. Also, the single quadrant system resulted in ANC insertion loss of 17.8 dB at the 630 Hz 1/3 octave band.

All of the studies indicated that active control of random broadband noise in ducts can be extended to higher frequencies by using either smaller duct dimensions (Part I), or cross-sectional partitioning (Studies II, III, and IV). The most impressive high frequency partitioning results came from the cross-shaped splitter (Study IV), but there was a trade-off of low frequency ANC insertion loss.

The application of this research to industrial noise control problems would be most useful for environmental noise from exhaust stack situations. (Although Slagley and Guffey (2006) applied the partitioning scheme successfully in a laboratory situation to underground coal mining equipment.) As discussed in Part I, there would be a concern for increased pressure requirement on the fan to either use a single smaller duct, (proportional to the duct diameter ratio raised to the 4.5 power), or many smaller ducts (proportional to the duct diameter ratio raised to the 1.2 power) (Guffey and Hickey, 1983).

Therefore, the more modest gains of the cross-sectional partitioning methods may be attractive if the noise control problem could be solved with the ANC insertion loss levels reported in this research. It should be noted that ANC actually was highly effective in every test except when it was unstable. The modest differences between ANC in the 18 inch duct alone compared to the partitioning interventions were due to the fact that the ANC on the 18 inch duct worked well in the first place. The 18 inch duct ANC system typically achieved 14 dB of insertion loss at higher frequencies. The partitioning treatments achieved 16 to 23 dB ANC insertion loss. At lower frequencies, both the 18 inch system and the partitioning systems achieved over 20 dB of ANC insertion loss (except the cross-splitter).

## CONCLUSION

The research presented here indicated that active control of random broadband noise in ducts can be extended to higher frequencies by using either smaller duct dimensions (Part I), or cross-sectional partitioning (Studies II, III, and IV). The most impressive high frequency partitioning results came from the cross-shaped splitter (Study IV), but there was a trade-off of low frequency ANC insertion loss.

Further research in this vein would be useful on the cross-shaped splitter method of partitioning. While losing some low-frequency control, the impressive insertion loss in the range of 8.1 to 17.8 dB from 315 to 1000 Hz may make that method more attractive for some specific industrial applications. Also, it would be useful to extend the diameter size study to 24 to 48 inches. One of the limitations of this research was that having an 18 inch duct did not seriously degrade the ANC performance. It would be better to start with a large duct that were so large that no ANC insertion loss could be achieved, then attempt partitioning strategies.

Active noise control has long been an area of interest for acousticians and noise control engineers. The hardware limitations and need for expertise in implementation have limited the industrial applications of ANC technology. One application to which ANC is particularly well-suited is noise control on exhaust stacks. ANC works well to reduce the low frequency "rumble" that can travel great distances and annoy neighboring communities. However, for broadband noise sources, even a combination of active and passive controls may fall short of complete broadband noise control. This research indicated that the use of either smaller ducts, or cross-sectional partitioning, can extend the frequency range of control of ANC methods to higher frequencies. By providing up to 17 dB of insertion loss at 630 Hz, ANC may become more viable as an option for industrial noise control issues.

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